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Valuing the carbon sequestration regulation service by seagrass ecosystems of Palk Bay and Chilika, India

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ABSTRACT

The regulatory ecosystem services in terms of carbon sequestration and storage by Indian seagrass ecosystems were coupled with their monetary values in the context of climate change mitigation in the seagrass meadows of Palk Bay and Chilika Lagoon, two major seagrass ecosystems of India. The results showed that the meadows acted as a net sink of atmospheric CO_2; however, they may also act as a minor source of CO_2 to the atmosphere depending on the degree of anthropogenic influence. The mean ecosystem productivity ranged between 6.31 and 11.9 kg C $ha^{-1}d^{-1}$, which is equivalent to the capture of 8.44 and 15.9 Mg CO_2 ha^{-1} $year^{-1}$. This captured carbon was apportioned primarily in sediments (129 Mg C_{org} ha^{-1} in top 1 m soil), which was much higher than the carbon stored as above and below ground biomass (0.20–0.96 Mg C_{org} ha^{-1} and 0.30–2.90 Mg C_{org} ha^{-1}, respectively). The economic valuation of regulatory ecosystem services in the form of C sequestration by an estimated 51,700 ha of total seagrass cover in India was largely dependent on the sequestration rates and the average social cost of carbon. The estimated values ranged between $ 1.02 million and $ 3.65 million per year. In addition, monetary values of the stored carbon in live biomass of Indian seagrass systems ranged between $ 0.45 million and $ 3.89 million, whereas, in the top 1 m soil it ranged between $ 109 million and $ 146 million. Detailed evaluations of various ecosystem functions considering the importance of the local variables may provide a better monetary estimate of these regulatory services.

1. Introduction

Seagrass ecosystems provide ecological services (climate change regulations, maintenance of marine biodiversity, regulation of quality of coastal waters, protection of the coastline, etc.) which are directly used or beneficial to humans. The economic value of seagrass can be measured through proper assessment of the services provided to the coastal biodiversity, fisheries, and wildlife tourism. Among the array of ecosystem services that seagrass ecosystems provide, the role as a significant sink for carbon is the most viable route to combat climate change (Hejnowicz et al., 2015). Furthermore, removal of nutrients from the ambient water column suggests the capability of seagrass ecosystems to provide an additional service of coastal water conditioning (Singh et al., 2015; Ganguly et al., 2017).

Seagrass meadows are associated with high net community production (NCP) with the global mean estimated to be around 6.70 t C ha^{-1} $year^{-1}$ (Duarte et al., 2013a). This is several times higher than NCP rates associated with Amazonian forests and North American wetlands, and underlines the importance of seagrass ecosystems to serve as a carbon sink (Duarte et al., 2010). Partitioning of the captured C is complex and may be distributed in different proportion into the sediment, water column, trophic food web and outside (export) the system. The time scale of C storage in the seagrass biomass is relatively shorter than in seagrass sediments. The most robust data suggest that the mean local C_{org} burial rates in seagrass meadows range between 1.2 and 1.38 t C ha^{-1} $year^{-1}$, which is equivalent to 30–50% of NCP (Kennedy et al., 2010; Duarte et al., 2013a, b). Additionally, seagrass meadows trap allochthonous material which includes large amounts of particulate carbon, and combined with their ability to bury carbon, the seagrass meadows enable storage of large amounts of carbon (Duarte et al., 2013b). The crucial roles of seagrass ecosystems in mitigating climate change have been ranked 8th in global importance by marine scientists (Rudd, 2014). In spite of the efficient capture and storage of C, blue carbon ecosystems, including seagrass rarely have been included in current mitigation and adaptation programs (Locatelli et al., 2014). India has proposed creation of an additional carbon sink of

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Table 1
Geographic location, vegetation type and other related information on the selected survey sites.

Station		Lat (N)	Long (E)	Bottom Vegetation	Depth (m)	Salinity conditions
Chilika	1	19°35′ 26″	85°13′ 26″	*Halophila ovalis* (~80% cover)	1.4	High seasonal fluctuation
Chilika	2	19°41′ 17″	85°17′ 47″	*Halodule uninervis* (~70% cover)	1.8	High seasonal fluctuation
Palk Bay	1	09°17′ 29″	79°07′ 44″	*Cymodocea serrulata (> 80% cover)*	2.1	Moderately stable
Palk Bay	2	09°29′ 05″	78°54′ 04″	Mixed seagrass bed *Thalassia hemprichii* (~60% cover), and *Syringodium isoetifolium;* (~30% cover)	1.6	Moderately stable

2.50–3.00 billion tonnes of CO_2 equivalent through additional forest and tree cover by 2030 in its Intended Nationally Determined Contribution (INDC). Blue carbon ecosystems, with their high carbon burial rates as compared to the terrestrial systems, though not specifically mentioned, could be a significant component of the proposed vegetative carbon sink.

Despite the high climate regulation capacity of seagrass ecosystems, their spatial extent continues to decline (Duarte et al., 2013a; Fourqurean et al., 2012; Lavery et al., 2013). During the past 70 years, the decline in seagrass extent has occurred at a rate of 0.9%year^{-1} (prior to 1940) and of 7% year^{-1} since 1980 (Waycott et al., 2009; Fourqurean et al., 2012; Duarte et al., 2013a). Globally, 24% of seagrass species are now classified as either threatened or near-threatened on the IUCN's Red List (Short et al., 2011). Although conservation and restoration of seagrass meadows are not covered under the existing carbon markets, efforts are being made to include blue carbon under the UNFCCC (Hejnowicz et al., 2015).

In India, seagrass meadows have been reported from both its shallow coastal waters and the offshore islands. Using satellite data and field surveys, Geevarghese et al. (2016) estimated the seagrass cover along India's coast as 517 km^2. The major areas are located along the east coast in Palk Bay (330 km^2), Gulf of Mannar (69 km^2), and Chilika Lagoon (85 km^2). Although lesser in extent, some seagrass patches have also been observed on the west coast in the Gulf of Kutch, Gujarat, and in the lagoons of Lakshadweep in the Arabian Sea, and the Andaman and Nicobar waters in Bay of Bengal. Fourteen species of seagrass have been identified from the Indian coast, belonging to seven genera, of which Palk Bay has the largest seagrass species diversity (Patro et al., 2017).

Globally, many studies have been carried out to understand the carbon regulatory mechanism in seagrass ecosystems, while only a few exist from India (Singh et al., 2015; Ganguly et al., 2017). Further, assigning a monetary value to biodiversity and to blue carbon is not currently covered by the UNFCCC and hence is not included in carbon trade. Most economists and climate scientists often consider the Social Cost of Carbon (SCC) as an underestimated value of the damages caused as a result of climate change impacts. However, countries are not required to account for it, as they are neither responsible for any increased emissions from blue carbon, nor benefit financially from blue carbon emission reductions or restoration. As a result, economic incentives are tilted in favour of converting blue carbon habitats to alternative uses from which parties can generate profits. However, in order to conserve these ecologically vital ecosystems, the Biodiversity Act 2002 of India emphasized the significance of measuring the economic value of biodiversity. The Act has identified a wide range of uses for such values; which include demonstrating the value of biodiversity when targeting biodiversity protection within scarce budgets, and determining the value of damage when biodiversity is lost. With the exception of a few studies on regulation services of seagrass in Indian waters (Singh et al., 2015; Ganguly et al., 2017), economic valuation barely exists.

The major seagrass meadows of India (Palk Bay and Chilika) are being monitored by the National Centre for Sustainable Coastal Management as an Ecologically Sensitive Area (ESA) of environmental importance under the Coastal Regulation Zone (CRZ) Notification, 2011. In this context, it also becomes essential to determine the economic valuation of the ecosystem services provided by this ecosystem. In the present study, a holistic approach has been taken to quantify the climate change regulatory services of seagrass of Palk Bay and Chilika and to assess the economic evaluation of carbon sequestration. In addition, this article attempts the evaluation of "seagrass carbon finance" based on current national and international climate policy frameworks.

2. Methods

2.1. Sampling

Two major seagrass ecosystems along the east coast of India viz. Palk Bay (10.2917° N and 79.3404° E) and Chilika Lagoon (19.7167° N and 85.3167° E), covering > 80% of the total seagrass area of the country, were studied to evaluate the ecosystem regulation through carbon sequestration and storage (Table 1). Chilika is a shallow lagoon, receiving significant monsoonal discharge during the wet season causing considerable changes in hydrological characteristics between the two seasons (Ganguly et al., 2015). Seagrass meadows are mostly restricted within central and southern sectors of this shallow lagoon (Priyadarsini et al., 2014). Palk Bay is a shallow basin with muddy substratum and limited riverine inputs with relatively stable saline characteristics throughout the year. Live coral reefs exist adjacent to the seagrass meadows, particularly in the southern part of Palk Bay (Manikandan et al., 2014). These two ecosystems were selected for the study as i) they represented a major share of healthy seagrass meadows in India, ii) display contrasting environmental characteristics, and iii) there is no study on evaluation of regulatory services through carbon sequestration.

2.1.1. Field sampling of water, sediment and biomass

Extensive spatial surveys were undertaken in May, 2016 to examine the seagrass cover, water column depth, and water quality of seagrass meadows in both Palk Bay (54 survey sites) and Chilika Lagoon (20 survey sites) for assessing the ecosystem carbon dynamics. On the basis of the spatial assessments, two representative locations from each ecosystem were selected for the determination of diurnal periodicity, net community productivity (NCP), and carbon storage of seagrass ecosystems (Table 1). Thick seagrass meadows in the near shore region (~2 m depth) in Palk Bay (seagrass cover 70–90%), and the seagrass dominated region in Chilika (seagrass cover 50–80%) were chosen for the diurnal study (Table 1). The vegetation type with percent seagrass cover at each location was measured using visual estimation technique (Krause-Jensen et al., 2004). Diurnal surveys were carried out during May 2016 (dry season) and December 2016 (wet season) in Palk Bay, whereas in Chilika, surveys were carried out during May 2016 (dry season) and September 2016 (wet season). Water samples were collected from the survey sites on an hourly basis for 24-h diurnal cycle to study the carbon dynamics of these meadows.

During both seasons, seagrass biomass samples were collected from mono-species beds of *Halophila* sp. and *Halodule* sp. at Chilika, and from *Cymodocea* sp. *Syringodium* sp. and *Thalassia* sp. beds at Palk Bay. Randomly selected six quadrates (0.25 m × 0.25 m) from each sampling site were used for estimating the species composition, and above

and below ground biomass. The collected seagrass samples were washed carefully with ambient seawater over a 1.5 mm mesh sieve to remove the attached sediments, and temporarily stored in labelled plastic bags in an ice box (maintained < 4 °C) until further processing in the laboratory.

Similarly, a total of six sediment cores (length up to 1 m) were collected from each of the selected stations at Chilika and Palk Bay. Core sampling was carried out using 1 m stainless steel corer with 7 cm diameter. Special care was taken while collecting the cores, to avoid any compression of the sediments, and a compaction correction factor (i.e., the length of sample recovery divided by the length of core penetration) was used to compensate for any intermittent compaction during sampling following Howard et al. (2014). The sediment cores were immediately sectioned at 5 cm interval *in situ*, and subsamples were placed in Zip-lock® plastic bags to prevent contamination. The sub-samples were placed in an icebox (< 4 °C), transported to the laboratory, where the sediments were freeze-dried and stored at 4 °C until further analysis.

2.2. Measurements of environmental parameters

2.2.1. Water quality

Water quality parameters viz. salinity, pH, temperature, dissolved oxygen (using optical probe), turbidity; photosynthetically active radiation (PAR) and chlorophyll-*a* were measured *in situ* at 0.1 m above the seagrass canopy at each site using pre-calibrated HYDROLAB Sonde. Inter-calibration of *in situ* measurements of chlorophyll and DO were also conducted using conventional methods (Grasshoff et al., 1999). The precision of O_2 measurements using O_2 optodes was < 0.1 μmol kg^{-1} under ambient conditions, and accuracy was within ± 3.0 μmol kg^{-1}. Analysis of the water samples was carried out in the laboratory within a week after sampling. Total alkalinity (TA) was measured by Gran titration using Autotitrator (Metler Toledo-Compact Titrator G20) and precision pH meter (DG115-SC). pCO_2 was calculated using CO2SYS program of Lewis and Wallace (1998), from *in situ* TA and pH (Dinauer and Mucci, 2017).

2.2.2. In situ measurements of net community production

Rate of community metabolism was quantified through *in situ* measurement of net community production (NCP), which corresponds to the difference between gross primary productivity (GPP) and community respiration (CR) as follows:

$$NCP = GPP - CR$$

Diel community metabolic rates (GPP, CR, and NCP) were estimated using the integrative open water mass balance approach for dissolved oxygen (Odum, 1956; Champenois and Borges, 2012; Peeters et al., 2016). As both the study areas (Palk Bay and Chilika) remained vertically isothermal, integrated O_2 content in the whole water column (~2 m) was used for computation of seagrass metabolism. Among other techniques to measure seagrass metabolism 'benthic chamber' method (Olivé et al., 2016) and 'DIC gradient' method (Tokoro et al., 2014) were also being preferred by several researchers with their respective advantages over the other. However, in the present study, we followed O_2 optode based (using a luminescence quenching principle without the need of any temperature corrections) mass balance approach, which has a strong agreement with the benthic chamber based measurements in seagrass community metabolism following Champenois and Borges (2012). More recently, Peeters et al. (2016) advocated the advantages of diel O_2-technique over other methods for measurement of independent community metabolisms in well mixed waters.

For measurement of discrete water column productivity (phytoplankton), light and dark BOD bottles filled with ambient water samples (in triplicate) were incubated for 24 h *interval* (Serret et al., 2015). Changes in oxygen concentrations over diel cycles were used to calculate water column gross primary productivity and community respiration for both seasons. All the measurements were carried out in triplicates and the computation for productivity was done by considering a 24-h cycle starting at sunrise of any given day viz. 6.00 a.m.

2.2.3. Estimation of carbon storage (biomass and sediment)

Calcareous epiphytes present in the seagrass biomass were removed by submerging the leaves in 10% HCl, followed by washing through distilled water in the laboratory. Seagrass collected from the quadrates (0.25 m × 0.25 m) were separated into above ground (leaves) and below ground (rhizomes, roots) tissues and estimated for the biomass by weighing the leaves, rhizomes and roots after oven drying at 60 °C to a constant weight. Mean value of six quadrates was considered and the biomass was expressed as mg dry wt. ha^{-1}. The sediment core subsamples were dried at 60 °C and homogenized for organic carbon analysis. Acid (HCl) treated sediment was combusted using CHNS Elemental Analyzer (Thermo Finnigan Flash EA1112) for the quantification of sediment organic carbon. The accuracy of this methodology was assessed by replicating the analyses using certified reference materials, (Soil Reference Material NCS, Thermo). Good to excellent precision were obtained (± 0.1–0.5%) for elemental carbon. Similarly, the carbon content in the above ground and below ground dried seagrass tissues were determined using CHNS Elemental Analyzer. Further, the carbon stocks in the seagrass biomass were calculated from the carbon content and biomass of seagrass species as given by Armitage and Fourqurean (2016). Sediment carbon stocks were estimated from the sediment organic carbon and bulk density of the sediment following Ganguly et al. (2017).

2.2.4. Statistical analysis

In order to determine the seasonal variations between various water and sediment parameters, within each ecosystem, one way ANOVA was performed in Minitab 16. Prior to the analysis, linear mixed effects models, with the plot as random factor (*lmer* function in the *lme4* package version 1.1–7 in *R* software package; Bates et al., 2015) were used to avoid pseudo-replication in the design for both factors. Additionally, one way ANOVA test was performed to examine the spatial and temporal variations in NCP for the two seagrass ecosystems. Linear regression analysis was carried out to explain the variability in the soil organic carbon with respect to above ground biomass (AGB) of seagrass (independent variable) in different meadows.

2.3. Valuation of carbon sequestration and storage

The social cost of carbon is defined as the estimated monetized value of damages caused by an additional unit tonne of carbon dioxide emissions or its equivalent released into the atmosphere. In other words, the social cost of carbon (SCC) denotes the value of avoided damages as a result of a unit reduction of carbon dioxide or its equivalent emissions. The basis for estimating the value of carbon sequestration and storage of coastal and marine ecosystems is to consider the sequestration potential of respective ecosystems and the market rate or the social cost of carbon. Nordhaus (2011) has given the conversion factors for monetizing carbon sequestration and carbon storage values of forest ecosystems for estimating the social cost of carbon. In the present study a revised version of the Dynamic Integrated model of Climate and the Economy (DICE, 2016R) model (Nordhaus, 2017) was used to estimate the social cost of carbon (SCC) for multiple countries including India (Table 2). The SCC estimation was based on the assumption that it is proportional to the discounted value of output in each region over the period between 2020 and 2050, discounted at a rate of 5% per year. The following empirical function was used to determine the economic value of blue carbon sequestered:

$$VC_i = SQ_i \times A_i \times SCC$$

where the value of carbon sequestered (VC) by a particular ecosystem

Table 2
Social Cost of Carbon for India (Nordhaus, 2017) estimated following the DICE-2016R model.

	Global	India
1 Tonne Carbon	\$114.43 (Rs7,630)	10.71 (INR714)
1 Tonne CO_2	\$31.21 (Rs2,082)	2.93 (INR195.4)

(i) is measured (as tonnes CO_2 e $ha^{-1}year^{-1}$) by the product of its rate of carbon sequestration (SQ) or carbon storage, area (A), and the chosen SCC. The social cost of carbon is primarily the rate of sequestration and the area of the ecosystem assessed converted into monetary values. *In situ* (each site) measurements on seagrass productivity, uptake and carbon storage in each system are described in the sections above. Additionally, the data set of productivity, uptake and carbon storage from previous studies by Singh et al. (2015) and Ganguly et al. (2017) were also included and averaged with the *in situ* observed data for the calculation of the total value of carbon sequestration for these two major seagrass ecosystems of India. As these two studied ecosystems contribute more than 80% to the total seagrass cover of the country, the results derived from the representative measurements were extrapolated to estimate the potential social cost of carbon for the country. All estimates have been converted to Indian Rupees (INR) using an average 2016 US Dollar exchange rate of Rs 66.7.

3. Results

3.1. Seagrass carbon capture and storage

The mean ecosystem productivity for the studied seagrass meadows ranged between 6.31 and 11.9 kg C ha^{-1} d^{-1}, which is equivalent to the capture of 8.44 and 15.9 Mg of CO_2 ha^{-1} $year^{-1}$. The seasonal variations in the net C flux from the seagrass ecosystems of Chilika and Palk Bay are given in Fig. 1.

Both the seagrass ecosystems (Chilika and Palk Bay) responded negatively to monsoonal freshwater flow with reduced ecosystem productivity and higher dissolved CO_2 concentrations in the coastal waters (Table 3). Significant seasonal variations in most of the water quality parameters (Salinity, pH, SPM, Chlorophyll-*a* (< 0.001) and DO (< 0.05)) were recorded in Chilika seagrass meadows, whereas for Palk Bay meadows variations were observed only for Chlorophyll-*a* and SPM concentrations ($p < 0.05$). Growth of benthic rooted plants such as seagrass is suppressed due to reduced light availability during monsoon creating a shift from benthic to pelagic primary production. This introduces large diurnal variations in oxygen conditions from high rates of photosynthesis during day followed by high respiration rates at night. In addition, oxygen consumption within the sediment increases following the deposition of easy degradable algal material on the sediment (Purvaja et al., 2008). The mean NCP (9.11 kg C ha^{-1} d^{-1}) calculated from these two systems were comparable to those reported from Puttalam Lagoon, Sri Lanka (7.0 kg C ha^{-1} d^{-1}; Johnson and Johnstone, 1995) but were nearly four times below the values (33.3 kg C ha^{-1} d^{-1}) reported from the Lakshadweep waters, India (Kaladharan and David Raj, 1989).

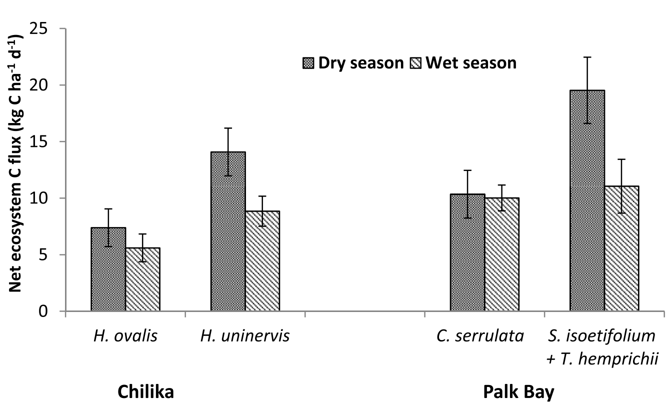

Fig. 1. Comparison of net community metabolism (± standard deviation) between two seagrass meadows in India.

Water column productivity, contributed by phytoplankton mostly remained < 10% of the net community production (benthic + water column), largely regulated by seagrass productivity. Slow growing seagrass ecosystems are associated with higher NCP in the dry season than the wet season, due to higher PAR, water temperature, salinity and lower dissolved nutrients. On the contrary, water column productivity dominated by fast growing phytoplankton community showed a reverse seasonal trend, with higher values during the wet season (Ganguly et al., 2017). Assuming C_{org} burial rates of 30–50% of the NCP (Duarte et al., 2010) the long-term C burial by Indian seagrass is estimated to be 2.73–4.55 kg C ha^{-1} d^{-1}.

Near surface carbon (top meter soil + biomass, Mg CO_2 ha^{-1}), susceptible to disturbance in the seagrass meadows was estimated for Chilika and Palk Bay ecosystems. The study indicated that carbon storage in the aboveground biomass of seagrass (range: 0.20–0.96 Mg ha^{-1}) was significantly lower than that in the below ground biomass (0.31–2.93 Mg ha^{-1}). Among the five species studied, *Cymodocea* sp. and *Halophila* sp. showed the highest and lowest biomass, respectively. Organic carbon in top 1 m soil in the seagrass meadows ranged between 107 and 143 Mg C_{org} ha^{-1}, with the highest and lowest values recorded from *Thalassia* sp. and *Halophila* sp. beds, respectively (Fig. 2). No significant seasonal variations in C content, either in the live biomass or in sediment ($p > 0.05$) were observed at the Palk Bay survey sites. In Chilika, however, there was a 30% and 18% reduction in seagrass biomass and sediment C content, respectively, during wet season, when compared to the dry season. Strong linear relationships between soil organic (Mg C/ha) carbon and seagrass AGB from different species were recorded in the present study (Table 4).

In comparison to the dry season, the mean NCP of the seagrass meadows was reduced by 33% at Chilika and 29% at Palk Bay, during wet season, largely attributed to the influence of freshwater. Comparison of stored carbon in the live biomass and top 1 m soil was made to estimate their relative contribution to the total carbon storage. In *Halophila* and *Halodule* sp. beds only 5% of the sequestered carbon was stored in live biomass (above and below ground), whereas 95% of the organic carbon was stored in the top 1 m of the sediment. Similarly, the live biomass of *Cymodocea* sp., *Syringodium* sp. and *Thalassia* sp. store 19%, 6% and 17% of the total sequestered C, respectively. Major proportion was stored in bottom sediments (mostly produced from *in situ* production and sedimentation of particulate carbon from the water column).

A conceptual diagram of the C flow and storage in the Indian seagrass ecosystems is given in Fig. 3.

3.2. Value of carbon sequestration and storage in seagrass ecosystems

There have been many studies in the past, assessing the economic value of seagrass meadows. One of the very first attempts at valuing seagrass meadows was made by Costanza and Folke (1997) where the value of the world's seagrass meadows was estimated at \$ 19,002 ha^{-1} $year^{-1}$ based on its regulating function of nutrient cycling. Subsequently, there have been many studies to assess a range of other regulating, cultural and provisioning services.

The mean estimates for SCC in peer reviewed studies are recorded to be \$ 80.0 per ton of Carbon, which is significantly lower than non-peer reviewed value of \$ 296 per ton of Carbon (Tol, 2011). Differences in SCC values are attributed to the discount rates, estimates of CO_2 emissions, the rate of global warming, population and economic projections and the overall models used. A recent study by Nordhaus

Table 3
Seasonal variation in mean water and sediment parameters of seagrass meadows in Palk Bay and Chilika (Mg represents Megagram).

Parameters	Chilika		Palk Bay	
	Dry season	Wet season	Dry season	Wet season
Water Temperature (°C)	30.1 ± 0.13	27.4 ± 0.61	32.3 ± 0.79	27.8 ± 1.00
Salinity	22.4 ± 8.29	5.57 ± 3.81	34.8 ± 0.25	31.6 ± 0.72
pH	8.07 ± 0.15	7.75 ± 0.26	8.26 ± 0.05	8.15 ± 0.04
Dissolved oxygen (μM)	231.0 ± 7.9	214.3 ± 3.8	207.6 ± 8.1	225.0 ± 15.3
p_{CO2} (μatm)	588 ± 80	614 ± 104	381 ± 109	395 ± 125
Suspended particulate matter (mg/L)	72.8 ± 15.9	136 ± 57.8	160 ± 14.9	60.5 ± 10.3
Chlorophyll-*a* (mg/m^{-3})	5.00 ± 3.10	3.72 ± 1.74	0.630 ± 0.12	2.23 ± 0.43
Sediment organic carbon (%)	0.98 ± 0.33	0.69 ± 0.22	1.01 ± 0.15	0.97 ± 0.19
Total seagrass biomass (Mg dry wt. ha^{-1})	6.10 ± 0.54	4.25 ± 0.45	24.2 ± 3.20	23.2 ± 2.92
Water column productivity (kg C ha^{-1} d^{-1})	0.56 ± 0.34	−1.81 ± 1.22	0.42 ± 1.08	0.87 ± 0.18

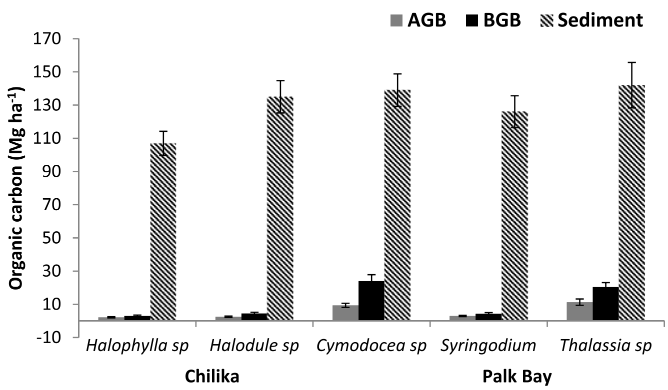

Fig. 2. Distribution of organic carbon in the seagrass biomass and underlying sediment column (susceptible carbon top 1 m, i.e.) in the studied ecosystems.

Table 4
Relationship between soil organic (Mg C/ha) carbon and AGB (Mg dry biomass/ha) for different seagrass species studied from Chilika and Palk Bay.

Species	Regression equation	r^2	N	p
Halophila sp.	Soil organic carbon = 16.747 × AGB + 68.755	0.67	12	< 0.001
Halodule sp.	Soil organic carbon = 21.846 × AGB + 76.255	0.39	12	< 0.001
Cymodocea sp.	Soil organic carbon = 6.933 × AGB + 72.007	0.78	12	< 0.001
Syringodium sp.	Soil organic carbon = 18.714 × AGB + 70.909	0.60	12	0.005
Thalassia sp.	Soil organic carbon = 4.7315 × AGB + 92.178	0.44	12	< 0.005

(2017), based on a revised DICE model (Dynamic Integrated model of Climate and the Economy) and using the 2010 price rate as a reference point, estimated the global SCC value to be $ 31 per ton of CO_2 for the current period (2015). The observed carbon sequestration rates from the two major seagrass meadows of India (for two different seasons) were extrapolated to estimate their possible regulatory services. For India with a 9% share of the global SCC values (at a rate of US 2.93/t CO_2), the estimated annual regulatory value of seagrass (51,700 ha) ranged between $ 1.52 million (INR 102 million) and $ 3.52 million (INR 235 million), depending on sequestration rates and average social cost of carbon (Table 5).

Similarly, the monetary values of the carbon stored (range 107.1–143.4 Mg C_{org} ha^{-1}) in the live biomass and in the top 1 m soil of the Indian seagrass system (51,700 ha) are estimated to be $0.45–3.89 and $ 109–146 million (INR 30–260 and INR 7270–9740 million), respectively.

4. Discussion

4.1. Ecosystem services and carbon sequestration

The economic valuation of services provided by ecosystems has been of key interest in promoting the importance of conservation and expansion of Marine Protected Areas in the country. Various international organizations such as the International Union for Conservation of Nature (IUCN) and World Bank, have advocated the relevance of assigning a monetary value to ecosystem services in order to better demonstrate the importance of such ecosystem services. Hejnowicz et al. (2015) took an initiative to quantify the global scale potential of seagrass in climate mitigation, conservation and poverty alleviation and demonstrated the prospects for developing blue carbon initiatives and payment for ecosystem service programs.

In the present study, the regulating services by these meadows from the two most important seagrass ecosystems of India were analyzed through an approach of its ability to sequester and store carbon per unit area. Similar to the earlier reports (Singh et al., 2015; Ganguly et al., 2017), the present study indicates that seagrass primarily acts as a net sink of atmospheric CO_2 and a significant storage of organic carbon. The estimated regulating service by Indian seagrass ranged between $29.4 and 68.1 ha^{-1} year^{-1}, and was relatively lower than the estimates given for Indian mangrove ($ 170–$ 240 ha^{-1} year^{-1} at $ 10/ton CO_2 equivalent) by Pasupalati et al. (2017).

Spatial comparisons of NCP between the seagrass meadows of Palk Bay and Chilika revealed significant variations (ANOVA, $p < 0.001$) which was mostly attributed to the differences in species diversity, density and associated environmental conditions. The highest NCP was recorded from the mixed bed of *Thalassia hemprichi* and *Syringodium isoetifolium.* Additionally, the inter-seasonal variations in both Palk Bay (ANOVA, $p = 0.003$) and Chilika ($p = 0.001$) was attributed to the temporal changes in the respective meadow's health under differential influences of environmental conditions. These results indicated that spatio-temporal changes in C sequestration rates due to various natural and anthropogenic influences may proportionately modify their regulatory services. Even though seagrass ecosystems have been identified as ecologically sensitive areas in the Coastal Regulation Zone Notification, 2011, in India, globally they constitute only 3% of the total coastal and marine ecosystem values according to The Economics of Ecosystems and Biodiversity (TEEB) database of environmental valuation studies (Van der Ploeg et al., 2010).

The present study may be considered as an effort for composing the valuation elements for ecosystem services (carbon sequestration) rather than a complete blue carbon monetization approach under the real scenarios. The spatio-temporal heterogeneity in carbon parameters and limited data availability from other seagrass meadows of India may cause considerable differences in the estimation of ecosystem specific regulating services. Extensive studies with denser spatio-temporal data

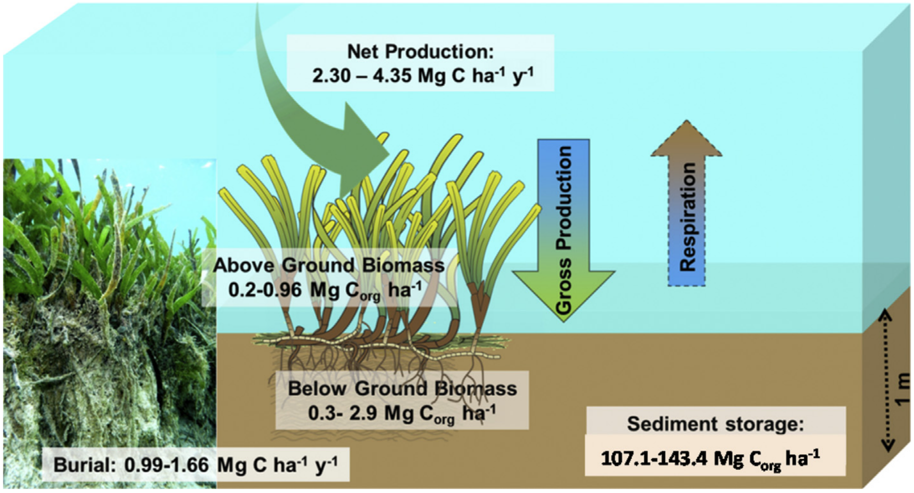

Fig. 3. Concept diagram of typical carbon flow in Indian seagrass ecosystems.

Table 5
Social Cost of Carbon (climate change regulation) of two major seagrass ecosystems of India.

Habitat	Annual carbon sequestration rate (tCO_2 equivalent ha^{-1} y^{-1})	Storage (t CO_2 equivalent ha^{-1})		Seagrass Area (in ha)	Economic Value of Carbon Sequestration per *year (values are expressed in 10^6 i.e. millions)*
		Living biomass	Soil organic carbon		
Seagrass Chilika	10.1–16.8	22.4	444	8500	\$0.239–0.418 (INR16.0–27.9)
Seagrass Palk Bay	14.1–23.3	88.5	497	33,000	\$1.32–2.21 (INR 88.2–148)

frequency from various benthic-pelagic environmental conditions, considering different beneficial services (water quality regulation, O_2 evolution, shoreline stabilization, etc.) could be useful to derive more realistic regulating values for the seagrass meadows of the entire country.

4.2. Variations in the stored carbon and associated economy

Owing to their integration with the other coastal and marine ecosystems, the health of seagrass meadows is often considered as an important indicator of the status of the coastal regions (Unsworth and Cullen, 2010). Degradation of unprotected seagrass meadows could counter the efforts against climate change by leakage of stored carbon back into the atmosphere. The relationship between soil organic carbon (Mg C/ha) and seagrass above ground biomass (AGB) for different species, observed in the present study, indicated the strong association of the former with the health of the meadows, which often is influenced by variability in temporal inputs (natural/anthropogenic) from the land. In addition to biomass density, changes in species compositions and richness may also influence the long term burial and storage of organic carbon and cause enhanced release of greenhouse gases and other organic and inorganic compounds, thus shifting the ecosystem from carbon sinks to carbon emitters.

The estimated climate regulatory ecosystem services by the seagrass meadows of Chilika and Palk Bay, calculated from the annual CO_2 sequestration rates, ranged from \$10.6–17.6 ha^{-1} y^{-1} and from \$ 15.0–25.0 ha^{-1} y^{-1}, respectively (based on an average SCC of \$2.93 for one tonne CO_2). These values were comparable with the carbon sequestration services provided by salt marshes and mangroves based on global sequestration rates (\$30.5 ha^{-1} y^{-1}) (Barbier et al., 2011). Similarly, considering the C present in seagrass biomass and the top 1 m soil (susceptible C), the total C stored per hectare for Chilika and Palk Bay were estimated to be worth \$1.37 and \$1.72, respectively, according to 2010 price levels. However, degradation of these ecosystems can have multiple negative impacts on the ecosystem services they provide. Global mean C emission as a result of seagrass degradation and loss (0.4–26% per year) was estimated as 522 Mg CO_2 ha^{-1} y^{-1} (Pendleton et al., 2012). Various natural changes (e.g. increase in sediment loads, water temperature, storms and storm surges, etc.) and human activities (e.g. nutrient inflows, fishing activities, etc.) already have been identified as the potential threats to these seagrass ecosystems in India (Thangaradjou et al., 2009; Singh et al., 2015). Further, the C pools in the top 1 m sediment, termed as 'near-surface' carbon, and becomes susceptible to degradation or disturbance. In the present study, a substantial decrease (~31%) in the 'near-surface' carbon in the seagrass meadows of Chilika Lagoon during the wet season reflected the negative effect of fresh water inflow on carbon sequestration. This markedly reduced the value of the climate regulating services provided by these meadows during the wet season because of the lower value of stored carbon as compared to that of the dry season.

4.3. Key risks and uncertainties in economic valuation of seagrass ecosystem services in India

A fundamental issue in environmental management and policy is uncertainty. Essentially, following three types of uncertainties have been identified for Indian seagrass ecosystems that underpin the valuation techniques:

- ***Scientific uncertainty:*** Understanding the relationships between ecological and economic parameters along with their interactions with the anthropological factors is not well established. The present study indicated the changes in the magnitude of seagrass C sequestration capacity with respect to the differences in space (between Palk Bay and Chilika seagrass) and time (between wet and dry seasons). Additionally, depending on the variable environmental uncertainties, a significant portion of seagrass NCP get exported and stored outside the meadows, that often remains unaccounted (Duarte and Jensen, 2017)
- ***Behavioural Uncertainty:*** The changes in policy or regulation affect the decisions or actions made by individuals or groups as any valuation technique assumes that all individuals and groups are rational entities and have full knowledge of their preferences.
- ***Value Uncertainty:*** Uncertainty exists regarding the choice of economic valuation techniques because each technique comes with its own conceptual, methodological and technical issues with the

values imposed by people on both market and non-market services.
- Additionally, chronic and sustained stresses such as sea-level rise, land use changes, altered hydrology, as well as sudden, discrete events such as cyclones, tsunamis, hurricanes etc. may cause uncertainty in the economic valuation of seagrass ecosystem services. For example, seagrass meadows in the Chilika Lagoon are surrounded by land and, thus, experience higher anthropogenic pressure. Cyclonic events affecting the area show strong seasonality. These uncertainties make the economic valuation and the assessment of the relative ecological/economic importance of the seagrass meadows less certain as compared to the more stable conditions in the meadows of Palk Bay.

4.4. Application of seagrass ecosystem service valuation

The role of environmental valuation methodologies in policy formulation is increasingly recognized by policy makers. The Convention on Biological Diversity's Conference of the Parties decision IV/10 acknowledges that “economic valuation of biodiversity and biological resources is an important tool for well-targeted and calibrated economic incentive measures” and encourages parties, governments, and relevant organizations to “take into account economic, social, cultural, and ethical valuation in the development of relevant incentive measures”.

The valuation of carbon sequestration and storage by seagrass in India, assessed in this study, can be useful for the monetary assessment of ecosystem degradations associated with the failure to prevent such losses in regulatory services. For instance, the monetary estimates for Indian seagrass meadows based on the average SCC could be useful to perform a cost-benefit analysis of future seagrass restoration in the coastal waters. Assigning a monetary value to regulatory services in seagrass ecosystems will help raise awareness of the importance of the services that upstream systems provide to downstream users. Valuation also helps in deciding different policy options, in identifying more efficient and cost effective alternatives, and in designing appropriate institutional and market (and non-market) instruments, including payment for ecosystem services (PES).

Seagrass ecosystem service valuation along with PES will be instrumental in designing well-defined mechanisms for multiple stakeholders to facilitate decision making. However, in the present study, out of the 14 species identified from the Indian waters, only four from two major ecosystems representing limited spatial coverage were assessed for climate regulation service. Extensive non-conservative estimates including the significance of species richness and diversity for carbon sequestration and storage with a broader geographical coverage can provide a more robust estimation of these services with limited uncertainty for the entire country.

5. Conclusions

Seagrass ecosystems provide several direct and indirect regulating services such as, C sequestration, water quality conditioning and checking soil erosion. In the present study, the prospects for financing seagrass conservation were solely examined using a carbon valuation approach that could help in capturing the benefits derived from climate regulation services, associated with carbon sequestration. The study further highlights that any natural or anthropogenic disturbances to the seagrass meadows may significantly reduce the stored carbon from the near surface and associated SCC per unit area. However, the valuation of these meadows with respect to coastal water conditioning and conservation of marine bio-diversity remains unaccounted. Therefore, realizing the “true” potential of seagrass meadows requires an international cooperation on two fronts: (i) combating the threats that are currently damaging the integrity of functioning seagrass ecosystems and (ii) inclusion of seagrass in informal climate change policies such as REDD +. Globally, a comprehensive policy framework such as Coastal Regulation Zone Notification (2011) of the Government of India is essential for conservation and preservation of key coastal ecosystems such as seagrass that are valuable in mitigating the effects of climate change.

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